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LCA OF WASTE MANAGEMENT SYSTEMS

The incorporation of waste prevention activities into life cycle assessments of municipal solid waste management systems: methodological issues

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Abstract

Background, aim, and scope Municipal solid waste (MSW) management organizations commonly address both waste treatment and diversion activities in their management plans, yet the application of life cycle assessment (LCA) to MSW rarely incorporates the effects of waste prevention activities (WPAs) in an explicit manner. The primary objective of this paper is to further develop the methodological options for attributional LCAs of MSW to address waste prevention, including product reuse.

Main features This article introduces the waste management and prevention (*WasteMAP*) LCA, a conceptual model that applies system expansion to generate a hybrid of the traditional product and waste LCA. The *WasteMAP* LCA, unlike the traditional LCA of MSW, can be used to compare functionally equivalent MSW management scenarios incorporating both treatment and prevention. This functional equivalence necessitates that waste prevention takes place through dematerialization. This form of WPA is analogous to waste management techniques such as landfilling in that it does not affect the functional output (product services) of MSW-generating product systems.

Results Integral to the *WasteMAP* LCA is the requirement that the sum of the MSW managed through treatment and prevention, and the level of consumption of product services contributing to MSW generation, are identical for each scenario. A partial abandonment of the zero-burden assumption is also required. Consequently, product life cycles associated with WPAs, excluding the waste treatment stages, comprise the 'upstream' component of the system boundary, while the 'downstream' component encompasses the waste treatment life cycle. *WasteMAP* also possesses primary and secondary functional units, with the former accounting for the amount of waste managed, and the latter depicting the product services provided by the product systems responsible for the waste targeted for prevention.

Discussion The *WasteMAP* LCA method can be used to identify in the results the burdens and avoided burdens attributed to waste prevention, recycling, biological and thermal treatments, as well as landfilling, within a particular MSW management system. This method also distinguishes itself through its ability to evaluate scenarios that target the prevention of particular waste streams to obtain downstream efficiency gains for the management of all waste materials.

Conclusions An attributional LCA of MSW can be applied to a wider array of possible waste management scenarios, including those with waste prevention, by expanding the system boundary, and in the case of waste prevention through dematerialization, by introducing an additional type of functional unit.

Keywords Life cycle assessment (LCA) · LCA methodology · Municipal solid waste (MSW) · Waste management hierarchy · *WasteMAP* (waste management and prevention) · Waste prevention

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1 Introduction

Life cycle assessments (LCAs) of municipal solid waste (MSW) management systems are undertaken to "optimise

the infrastructure system for managing a given amount and composition of waste" (Coleman et al. 2003) and often used to evaluate the validity of the waste hierarchy in identifying those waste management techniques with the lowest environmental emissions and impacts. Waste prevention and product reuse, the first two components of the waste hierarchy, respectively, are usually omitted from these evaluations (Ekvall et al. 2007).

Municipal solid waste managers who focus entirely on the 'end of life' stage of waste management, that is, once the waste has already been generated, will not succeed in curtailing per capita waste generation, which has increased by 35% in OECD countries since 1980 (OECD 2007). Municipalities have had little control over the policies and interventions that promote waste prevention and product reuse (McKerlie et al. 2006) because these policies are usually the purview of higher levels of government. Recently, cities such as Toronto, Canada have nonetheless attempted to enact policies such as financial incentives for citizens to bring reusable mugs and shopping bags to stores (City of Toronto 2008), in order to reduce waste generation and promote product reuse.

Ideally, producers of material goods attempt to design and/or select product systems that minimize environmental burdens, including solid waste, over the product life cycle. However, MSW managers have a different perspective, focusing on the burden of particular products or waste streams on the MSW management system as a whole, a view that is not captured in traditional product LCAs. MSW managers commonly deal with the system-wide effects of changes in processing efficiency and cost, the quantity of material residue generated during sorting and treatment, and the contamination levels of material feedstock for recycling (e.g., Lantz 2008). Although methods, such as improved sorting technologies, can be applied to address these MSW management issues, the targeted prevention of particular MSW streams can also be considered.

Integrated waste management, commonly perceived as the current standard of practice for waste management, is deemed to address waste treatment, prevention, and reuse (McDougall et al. 2001). However, the LCA of MSW management and the theme of waste prevention have tended to remain isolated from one another in the published literature. Exceptions include Coleman et al. (2003); Ekvall et al. (2007) and Olofsson et al. (2004), which allude to the potential for LCAs of MSW to be capable of evaluating waste prevention activities (WPAs) along with waste treatments. The apparent aversion to considering waste prevention as a form of waste management in LCAs of MSW could perhaps be attributable to the difficulty in answering the question: "Can one manage waste that has not been generated?" The fact that this issue has been alluded to in academic publications suggests that the answer to this question is in the affirmative. Most importantly, the WPA is a management process that is not applied to absent waste. The absence of waste is a consequence of the WPA. Therefore, the LCA practitioner can make the apparent philosophical leap to regard waste prevention as functionally equivalent to waste treatments in multi-material MSW LCAs.

Waste prevention has long been a subject of academic interest. Several authors have examined policies to encourage waste prevention behavior by households and industries (e.g., De Young et al. 1993). Of particular importance is the paper by Salhofer et al. (2008), which produces estimates of the waste prevention potential of five different measures (addressing advertising material, beverage packaging, diapers, food waste, and 'big events'), using Vienna, Austria as a case study. Examples of the waste prevention measures considered include the refusal of unsolicited advertising and the replacement of one-way packaging with refillable packaging. The authors estimate that each measure is capable of producing an approximate 10% reduction in the size of the relevant waste stream. With the debatable exception of waste prevention through the refusal of advertising material, the estimates by Salhofer et al. (2008) are based upon the proviso that a reduction in the unit mass of a product does not decrease the consumption of the service(s) provided by that product. 'Dematerialization' is an expression that is commonly used to represent this form of waste prevention, and has been defined by Van Der Voet et al. (2004) as the "process of fulfilling society's functions with a decreasing use of material resources over time." The residents of a municipality in which a WPA through dematerialization is undertaken would experience no apparent reduction in standard of living.

It seems likely that published LCAs of MSW rarely compare scenarios that manage different quantities of MSW because the scenarios would be subject to different functional units, thus violating the ISO 14044 international standard which states the requirements and guidelines for LCA (ISO 2006). One possible exception would occur if the functional unit no longer depicts a fixed quantity of MSW managed (e.g., the tonnage of MSW treated per year), but simply the amount of MSW generated in a particular municipality or region, which is assumed to vary in each scenario. In Cleary's (2009) review of 20 published LCAs of multi-material MSW management systems, only one LCA (Rodriguez-Iglesias et al. 2003) compares MSW management scenarios that have different total quantities of MSW collected from the same population, although LCAs by Mohareb et al. (2008) and Olofsson et al. (2004) also include scenarios with different MSW quantities. Rodriguez-Iglesias et al. (2003) and Mohareb et al. (2008) neither account for the upstream benefits of waste prevention, nor address whether or not the types of product

services supplied to the population differs for each MSW management scenario. In contrast, Olofsson et al. (2004) do account for the upstream benefits, and employ a consequential LCA methodology (see Section 4.2) inasmuch as the effects of waste prevention on markets for recyclable materials are addressed. However, none of these studies attribute any potential environmental burdens to the implementation of a WPA.

Waste managers and policy developers have lacked an effective tool to help with the evaluation of waste prevention activities in LCAs of MSW, with the significant exception of the US Environmental Protection Agency's (EPA's) WAste Reduction Model (WARM). WARM can provide the user with life cycle data on a waste management system's energy and GHG savings resulting from the source reduction of 34 different materials or categories of materials (US EPA 2006). WARM estimates the effects of waste prevention by decreasing the waste inputs into the waste management system and subtracting from the reference scenario the emissions from the product life cycle of the prevented MSW. The LCA practitioner arbitrarily defines the level of waste prevention desired for each scenario, without needing to maintain an equivalent set of product services for the population. For example, the LCA practitioner can compare the life cycle emissions of the reference MSW management scenario with those of a scenario in which the MSW from the disposal of 1,000 computers is eliminated. Also of potential significance is WARM's omission of the effects of each WPA on the treatment of the residual MSW streams.

2 Research objectives

In light of the claim by Ekvall et al. (2007) that the traditional LCA model used for MSW management systems is inadequate to address changes in the quantity of waste resulting from WPAs, this paper addresses (1) how the LCA practitioner can incorporate the effects of WPAs in an LCA of a waste management system; and (2) how, in such an LCA of waste, the LCA practitioner can compare waste prevention and treatment activities on a functionally equivalent basis. Section 3 of this article briefly reviews the various forms of waste prevention. Section 4 examines the existing capabilities of product and waste LCAs, as well as consequential LCA, to address waste prevention, relative to their respective system boundaries. Section 5 introduces the Waste Management And Prevention (*WasteMAP*) life cycle assessment model, which is conceived as a method to undertake an attributional LCA of MSW with the capability of evaluating the environmental performance of MSW management scenarios incorporating all of the components of the hierarchy of waste management, including waste prevention, product reuse, recycling, and the various forms of waste treatment.

3 Types of waste prevention activities

Waste prevention refers to activities undertaken to reduce the mass, volume or toxicity of products or materials consumed, and later discarded, through changes to their "design, manufacture, purchase, or use" (US EPA 1999). The hierarchy of waste management identifies waste minimization or prevention as the most desirable form of waste management, relative to its environmental performance, followed by product reuse, recycling, energy recovery, and landfilling (Price and Joseph 2000). Although listed separately in the hierarchy of waste management, product reuse can be considered a form of waste prevention since it almost always results in a reduction in the amount of waste requiring collection (Laner and Rechberger 2009). References to waste prevention in this article also encompass product reuse activities.

WPAs may be undertaken by consumers, producers, and/or MSW managers and can be regulated or otherwise facilitated by government and industry through pricing adjustments, regulation, and other means (Salhofer et al., 2008). Consumers can reduce their demand for goods through their purchasing decisions and by using goods more productively. Producers can change the design of a product (e.g., the amount and type of materials required, replacement life and service life) (Cooper 2005, McKerlie et al. 2006) and the production system, resulting in lower environmental emissions, while maintaining product performance.

Table 1 describes and provides examples of the various types of WPA. It also lists their properties both in terms of the potential effects of each WPA type on product service (s), and on the presence of alternate product system(s) that would generate additional MSW for treatment. WPAs in accordance with the US EPA's definition of waste prevention, which explicitly assumes that WPAs reduce waste generation, are listed and classified as WPA types 1-6 in Table 1. WPA type 1 characterizes the decrease in the amount of waste generated as a reduction in the quantity of material consumed, without product service substitution. WPA types 2-6 represent dematerialization, which ensures that less MSW is generated, without decreasing the functional outputs associated with the materials entering the MSW management system.

MSW can also be prevented at the collection stage of the waste management life cycle. On-property residential waste treatment and the storage of waste products and materials (WPA types 7 and 8) may be considered forms of waste prevention, although it is perhaps more justifiable to

Table 1 The properties of each type of waste prevention activity

Type of waste prevention activity (WPA)	Effect of WPA type on product service(s)	Presence of alternate product system(s) that contribute additional MSW for treatment	Example(s)
WPA-1 reduction in material consumption without product service substitution	Reduction in quantity of product services (no substitute product services provided)	No	Reduced generation of “junk mail”
Dematerialization			
WPA-2 reuse of a disposable good	Substitution of functionally equivalent product services	No	Reuse of a disposable shopping bag
WPA-3 substitution of a service, provided by a capital good, for a disposable good	Substitution of functionally equivalent product services	Yes (capital good)	Drying of hands by means of hand dryers instead of hand towels, drinking water supplied from water faucets instead of bottles, newspaper articles available online instead of printed on newsprint
WPA-4 substitution of a reusable good for a disposable one	Substitution of functionally equivalent product services	Yes (substitute reusable good)	Substitution of refillable glass wine bottles for disposable ones, substitution of reusable shopping bags for disposable ones
WPA-5 lightweighting of a good	Substitution of functionally equivalent product services	Yes (substitute disposable good)	Substitution of lightweight plastic containers for glass ones (both containers are single use)
WPA-6 lengthening the useful lifespan of a durable good	Substitution of functionally equivalent product services	Yes (substitute durable good)	Increasing the useful lifespan of a refrigerator through improved design
Waste prevention at collection			
WPA-7 on-property residential waste treatment	No effect	No	Backyard composting, grasscycling
WPA-8 storage of waste products and materials	No effect	No	Storage of obsolete appliances

consider them as forms of waste diversion since the waste is produced, although it will not be collected for the MSW treatment system. Since waste is generated, there is no effect on the quantity of product services supplied (see Table 1). Product storage, while delaying the treatment of waste, increases the future material liability of a MSW treatment system. This circumstance places importance on the LCA practitioner’s assumptions that pertain to discount rates and future MSW collection and treatment capabilities. Data on the “hibernating” (stored) portion of products and materials are rare (Brunner 2004).

4 Attributional and consequential approaches to waste prevention and LCA

A reduction in the MSW inputs to the waste management system is inherent to the concept of waste prevention. Waste would have been generated in the conventional manner had it not been for the employment of a particular decision to undertake waste prevention. From this perspective, it would appear that the consequential LCA method is the only approach that is appropriate to evaluate the impacts from reducing MSW inputs. However, within the hierarchy of waste management, waste prevention is considered a form of waste management that is functionally equivalent to others such as landfilling and recycling. From this alternative viewpoint, it is possible to employ the attributional method when undertaking an LCA of MSW that incorporates WPAs.

4.1 The attributional approach

The attributional LCA is used to describe a system and its environmental exchanges (Rebitzer et al. 2004). It is classified into the traditional product and waste management forms, each having different system boundaries. Both forms possess deficiencies in addressing WPAs.

4.1.1 The traditional product LCA

Traditional product LCAs can play an important role in evaluating the net environmental performance of WPAs and are pursued to “optimise a specific product life cycle” (Coleman et al. 2003). They can be used to estimate the differences in the environmental emissions or impacts between product systems, one generating less waste than the other, per unit of functional output supplied. A product

system, which is a "collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product" (ISO 2006), commonly includes raw material extraction, product manufacture, distribution, use, and disposal (Coleman et al. 2003).

A product LCA addresses the waste management stage only for the product studied and does not account for the potential effects of the removal or reduction in size of a waste stream on the entire MSW management system. Thus, it does not evaluate significant effects from the prevention of numerous "problematic materials" that are known to create collection, sorting and processing difficulties that detract from the efficiency of MSW management, and reduce the quality of recycled material. Examples include polylactide (PLA) biodegradable plastics, opaque polyethylene terephthalate containers and waxed cardboard (Solid Waste Management & Recycling 2008).

Recent examples of product LCAs that compare product systems which generate different quantities of waste include Aumônier and Collins (2005), who evaluate the environmental performance of reusable and disposable diapers, and Humbert et al. (2009), who compare plastic and glass packaging for baby food. It is uncommon for product LCAs to provide estimates of the net environmental emissions per ton of waste prevention. Instead, the emissions are compared for the different means to supply the same functional unit which reflects the primary use of the good.

4.1.2 The traditional LCA of MSW

A traditional LCA of MSW, encompassing waste collection, transportation, sorting, and treatment until inert or recycled, can be used to evaluate the life cycle impacts of a waste treatment system in which a particular waste stream is eliminated or reduced in size due to a WPA. It does not account for the net upstream impacts from implementing the WPA, nor the possible substitute product system(s) necessary to maintain an equivalent level of product services to the population under each MSW management scenario.

Ideally, all investigated product systems for an LCA begin at the same point—raw material extraction. However, Buttol et al. (2007) claim that "all life cycle stages prior to the product becoming waste can be omitted if they are common to all the subsequent waste management options." This curtailment of the LCA system boundary, also known as the zero burden approach, simplifies the assessment and allows the LCA to focus on waste treatment. Indeed, Wilson (2002) regards the LCA of MSW as an "end of pipe" model because it cannot address waste minimization or levels of material consumption.

A traditional LCA of MSW can incorporate waste prevention by simply excluding the MSW that is prevented, provided that the following criteria are met: (1) the LCA results for the MSW management system are not compared with those of an alternative waste management scenario; and (2) there are no significant additional and/or avoided upstream environmental burdens caused by the implementation of the WPA.

If the first criterion is violated, the MSW management scenarios will not use identical functional units, which conventionally depict the quantity of the MSW inputs. If the second criterion is not met, the system boundary of the traditional LCA of MSW will exclude the significant environmental emissions from the unit processes comprising the product system(s) targeted for prevention.

4.2 The consequential LCA

Should the objective of the LCA be the accounting of the economy-wide effects of implementing a WPA on the life cycle environmental emissions of a MSW management system, consequential LCA is the most appropriate method of analysis. Although the 2006 *International Organization for Standardization* (ISO) requirements and guidelines for LCA do not recognize the methodology associated with consequential LCA, this LCA type has been described in numerous publications, such as Ekvall and Weidema (2004), and Rebitzer et al. (2004). A consequential LCA is "a model of causal relationships originating at the decision at hand" (Ekvall and Weidema 2004), addressing the economy-wide effects of a change in the functional outputs and inputs on material and energy flows to and from the environment (Curran et al. 2005). Thus, it has a much larger system boundary than an attributional LCA because it also addresses significant flows outside of the MSW management life cycle. Unlike the attributional LCA, this method addresses the marginal effect of a change. There is no need to include within the system boundary those unit processes that would not be affected by the WPA. The functional unit of a consequential LCA would be the amount of waste prevention one intends to undertake.

5 The *WasteMAP* life cycle assessment

The *WasteMAP* LCA is proposed as a conceptual model to be used to facilitate the comparison of MSW management scenarios incorporating waste prevention and the various methods of waste treatment. The amount of MSW managed through treatment and/or a WPA, as well as the functional output of the products that would become MSW, defined by primary and secondary functional units (see Sections 5.2.1 and 5.2.2), remain constant in all comparative waste

management scenarios. The *WasteMAP* LCA method is attributional inasmuch as its objective is the comparison of the environmental performance of various MSW management scenarios. Unlike *WasteMAP*, none of the LCA methods described in Section 4 can be used to evaluate multi-material MSW management scenarios incorporating all of the components of the hierarchy of waste management.

In the *WasteMAP* LCA, waste prevention through dematerialization (WPA types 2-6 from Table 1) is considered a functional equivalent of MSW treatment and disposal methods, such as incineration and landfilling. It would not be appropriate to consider waste prevention through reduced consumption (WPA-1) as a functionally equivalent method of managing MSW because waste treatments do not affect the composition and magnitude of product services supplied to the population by waste-generating product systems. Product services generated from the waste treatments (e.g., electricity from MSW incineration), are exempt from the functional equivalence condition, although, when using the "avoided burden" approach (see Section 5.1), their beneficial environmental impacts must be accounted for as compensatory processes. Moreover, WPAs of types 7 and 8 may require the incorporation of additional product systems within the *WasteMAP* system boundary (e.g., a backyard composter).

The following sections describe the methodological characteristics of the *WasteMAP* LCA, including the system boundary, functional units, the functional equivalence of product systems, waste flow, and environmental emission accounting.

5.1 System boundary

System expansion permits the *WasteMAP* LCA to attain characteristics of both the product LCA system boundary and that of the LCA of MSW. Since there are numerous examples of WPAs which are not influenced by the actions of MSW managers, it is neither feasible nor desirable to account for all of them within the system boundary of the *WasteMAP* LCA of MSW. Thus, it is necessary to distinguish between WPAs that are implicitly included in MSW management scenarios, and "additional WPAs," which are explicitly included within the *WasteMAP* system boundary, with their net upstream and downstream benefits taken into account. A simplified depiction of the system boundary of the *WasteMAP* LCA is illustrated in Fig. 1, which uses a material substitution WPA as an example. This system boundary varies with the types of WPAs included in each scenario (see Table 1).

WasteMAP's upstream component has a system boundary similar to a product LCA (raw material extraction, processing, manufacturing, transportation, and use), although excluding the waste treatment stages. Its downstream component includes the collection, transportation, sorting, treatment, and disposal of the many MSW streams that enter the MSW management system. The upstream component of *WasteMAP* illustrated in Fig. 1 addresses only the product systems, excluding the waste treatment stages, that are potentially affected by WPAs: the targeted product systems (TPSs) and the alternate product systems (APSs). If applying the "avoided burden" approach

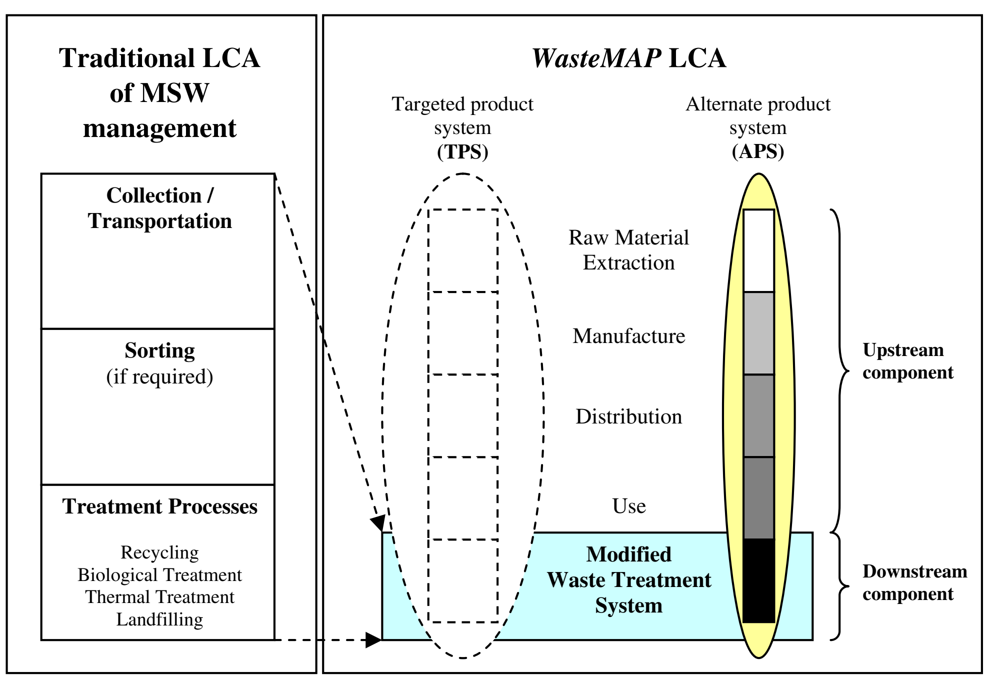

Fig. 1 Basic system boundary of the *WasteMAP* LCA. Note: some graphical elements of Fig. 1 were derived from McDougall et al. (2001)

(Frischknecht and Jungbluth 2007), the former refers to the product systems that are subtracted from the total MSW subject to treatment, while the latter depicts the product systems that may need to be added to the total MSW. Accounting for the impacts of TPSs and APSs can be a very complex endeavor, as they may include product systems for new capital, products, and services. MSW and upstream wastes can potentially be generated as a direct consequence of implementing a WPA which fully maintains the types of product services supplied to the population. The differing widths of the TPS and APS in Fig. 1 are intended to illustrate that the amount of waste removed from the MSW treatment system must be greater than the amount added to it.

If an LCA of MSW would evaluate waste management scenarios with different quantities of waste, such as those which account for WPAs, Ekvall et al. (2007) claim: “It is reasonable to demand that such studies include the environmental burdens associated with the production of all the materials that eventually become waste.” Although acquiescing to this demand could produce the ideal system boundary, it may not be necessary. The LCA practitioner can minimize data requirements by maintaining the zero burden assumption for those product systems unaffected by WPAs and applying system expansion to account for the avoided and additional burdens of the TPSs and APSs. The primary methodological complication of this approach is evident in cases in which the TPSs or APSs possess significant co-products, possibly resulting in an asymmetry. In order to ensure that the single product output of interest, measured by the secondary functional unit (see Section 5.2.2), remains isolated, the LCA practitioner can subtract compensatory single output processes. An asymmetry ensues if the sum of the impacts from the individual processes associated with the product output of interest and the co-products is not identical to the impacts from the original multi-output processes of the TPSs and APSs. One method to avoid such an asymmetry is to apply an allocation.

5.2 Functional units

The functional unit provides a common basis for LCA result interpretations and comparisons (Rebitzer et al. 2004). Although this concept is defined as the “quantified performance of a product system for use as a reference unit” (ISO 2006), the ISO’s definition requires the substitution of ‘waste management’ for ‘product’ in an LCA of MSW. The functional unit of a product LCA is defined by the output of the system, whereas that of an LCA of MSW is defined in terms of the system’s input (McDougall et al. 2001). Functional units for the *WasteMAP* LCA are analogous to those of product and waste management LCAs. Primary and secondary functional units ensure both a fixed amount of MSW managed in each scenario, as well as identical reference flows of functionally equivalent product services.

5.2.1 Primary functional unit

The primary functional unit of the *WasteMAP* LCA is the amount (mass or volume) of material addressed by the MSW management system on an annual basis. It is identical for all MSW management scenarios and is equal to the sum of the upstream primary functional unit (UPFU) and the downstream primary functional unit (DPFU). The UPFU is defined as the net amount of material left out of the MSW treatment system due to WPAs, whereas the DPFU tracks the amount of MSW collected and treated under each scenario. Since waste management scenarios that are considered functionally equivalent can differ in the amount of waste prevention undertaken, they need not have identical UPFUs and DPFUs.

The amount of solid waste generated upstream in product life cycles, including the mining overburden removed during raw material extraction, tends to greatly surpass the post-consumer waste (Washington State Department of Ecology 2003). The decision of whether or not to incorporate these upstream wastes in the primary functional unit would tend to be of high significance to the LCA results. Thus, the LCA practitioner may wish to include in the primary functional unit not only the residential waste managed through prevention and treatment, but also the upstream changes in the institutional, commercial and industrial waste resulting from the WPA(s) (see Section 5.3). When considering the mass equivalence of each waste management scenario, all of these waste types would be taken into account. Consequently, some WPAs, deemed equivalent in terms of the total mass of waste prevented, may not result in the prevention of the same amount of residential waste. The MSW management scenarios would not be equivalent from the perspective of the residential waste manager because the amount of waste collected and treated for each would differ.

5.2.2 Secondary functional unit

Product services supplied to municipal residents can often be delivered through alternative means and reduce total MSW generation. In the *WasteMAP* LCA, the product systems that provide these services are depicted by the TPS and the APS (see Section 5.1). Analogous to functional units in product LCAs, *WasteMAP*’s secondary functional units are used to ensure that MSW management scenarios subject to comparison will supply functionally equivalent product services to the residents of the municipality.

Consequently, the measured product services of TPSs are equivalent to those of the replacing APSs. The reference flows of the product systems added and removed from the MSW treatment system must also remain identical within each MSW management scenario.

Secondary functional units are only applicable when scenario comparisons address waste prevention in the form of dematerialization (i.e., WPAs 2-6 from Table 1). For example, a secondary functional unit can depict the function of supplying packaged juice to the residents of a municipality in a particular year. The means of delivering such a product service (e.g., a plastic or glass juice container), can differ. However, the reference flows of the TPSs and APSs that depict the quantity of packaged juice supplied to the population in each respective MSW management scenario would be equal.

It is not necessary for the LCA practitioner to define secondary functional units for the product functions associated with each MSW stream, but only to those wastes which are affected by WPA types 2-6. Secondary functional units cannot be applicable to waste management scenarios that incorporate WPA-1, since there would be no replacement product service provided. For this WPA type, MSW management scenarios cannot be compared with the reference MSW management scenario on a functionally equivalent basis.

There are two exceptions in which MSW scenarios under *WasteMAP* do not require a secondary functional unit to ensure the functional equivalence of product services: (1) the TPSs supply product services that are deemed unwanted by certain segments of the population (e.g., unaddressed advertising); and (2) the removal of waste from the MSW treatment system does not decrease the quantity of product services supplied to consumers (e.g., grasscycling).

The properties of a product are related to its functionality, technical quality (stability, durability, ease of maintenance), additional services rendered, esthetics, image, economic costs, and specific environmental properties (Weidema et al. 2004). Therefore, consumers may not always receive identical or equivalent product services when implementing waste prevention through product substitution (Weidema et al. 2004). For example, the lightweighting of glass bottles could result in an increase in the frequency of bottle breakage. Similar to the functional unit in comparative product LCAs, the only product property of significance is measured by the secondary functional unit, since not all of the properties are used or are necessary to carry out the product service required of it (Cooper 2003).

In assessing the waste prevention potential of WPAs, the LCA practitioner has to evaluate whether or not the consumer views the replacement product service as a reasonable substitute for the original. He/she must also account for the effect of consumer habits on the performance and lifetime of each product system (Günther and Langowski 1997). For example, if the primary reason for a consumer to replace a particular durable good is esthetic, an increase in product durability will have little or no impact on the amount of waste generated. Should the targeted product system encompass more than one significant function, the effects of the additional functions could be subjected to an allocation procedure or a boundary extension (Cooper 2003).

5.3 Waste flows

The net flows of waste relative to the default quantity of residential waste generated may be calculated through the application of Eqs. 1–3. Default residential waste generation in the reference *WasteMAP* scenario is the amount of residential waste (mass or volume) generated in the municipality of interest in the absence of additional WPAs, classified by product/material type, with the types of units used to depict mass or volume left to the discretion of the LCA practitioner. In contrast, net residential waste generation (RNET) takes into account the effects of additional WPAs on the default residential waste generated, usually on an annual basis. For each scenario, the cumulative net residential waste generation, irrespective of composition, is calculated in Eq. 1, assuming a total of n WPAs:

$$\mathrm{RNET} = \sum_{\mathrm{WPA}=1}^{n} \mathrm{RAPS}_{\mathrm{WPA}} - \sum_{\mathrm{WPA}=1}^{n} \mathrm{RTPS}_{\mathrm{WPA}} \qquad (1)$$

where RAPS is the residential waste generation potentially added to the MSW treatment system due to WPAs, while RTPS is the residential waste subtracted from the MSW treatment system. In order for net residential waste prevention to take place, RNET must be less than zero.

Although the *WasteMAP* LCA is conceived as a model for residential MSW management systems, the LCA practitioner may wish to account for the potential of WPAs to affect the production of upstream industrial, commercial and institutional (ICI) solid waste, including the eventual disposal of capital equipment. The cumulative net ICI waste generation (ICINET), irrespective of composition, is calculated by Eq. 2, assuming a total of n WPAs:

$$\mathrm{ICINET} = \sum_{\mathrm{WPA}=1}^{n} \mathrm{ICIAPS}_{\mathrm{WPA}} - \sum_{\mathrm{WPA}=1}^{n} \mathrm{ICITPS}_{\mathrm{WPA}} \qquad (2)$$

where, ICIAPS is the additional ICI waste that is potentially generated upstream, and ICITPS is the upstream ICI waste

that would have resulted from the production of the product system(s) subtracted from the MSW stream due to the WPAs.

Net waste generation (WNET), which takes into account the flows of residential, industrial, commercial, and institutional waste is calculated as follows, assuming that the WPAs in Eqs 1 and 2 are identical:

$$\mathrm{WNET} = \mathrm{RNET} + \mathrm{ICINET} \tag{3}$$

5.4 Environmental emissions

Equation 4 is used to calculate the environmental emissions of a *WasteMAP* LCA scenario, assuming that the implementation of n WPAs has no effects on the waste treatment system for the remaining MSW:

$$\mathrm{WMP} = \mathrm{REF} - \sum_{\mathrm{WPA}=1}^{n} \mathrm{TPS}_{\mathrm{WPA}} + \sum_{\mathrm{WPA}=1}^{n} \mathrm{APS}_{\mathrm{WPA}} \tag{4}$$

where WMP represents a particular environmental emission from a *WasteMAP* LCA scenario that includes WPAs, REF symbolizes the emission from the reference waste management scenario that lacks WPAs, TPS signifies the environmental emission from each reference flow of product systems subtracted from the MSW treatment system, and APS represents the environmental emission from each reference flow of alternate product systems that generate less waste.

The circumstance depicted in Eq. 4 is perhaps unlikely to be representative of the effect of implementing WPAs because WPAs change the composition and quantity of waste collected for treatment, which can generate effects throughout the MSW management system. Equation 4 is representative if the MSW streams associated with the TPSs and APSs are collected, sorted, and treated separately from the remaining MSW streams, such as used containers collected through a deposit-return system.

WasteMAP LCA scenarios depicted by Eq. 4 are inappropriate if the presence of WPAs results in significant effects upon: (1) the efficiency of the collection, sorting, processing, treatment, and disposal components of the MSW management system; (2) the overall contamination levels of collected materials for source-separated organics and recycling programs; (3) the physical and/or chemical reactions between the remaining MSW streams undergoing treatment; and (4) the quality of the processed waste material. Many of these effects are associated with the presence of so-called "problematic materials" for recycling programs (Waste Diversion Ontario 2009) and source-separated organics treatment programs.

If the result from Eq. 5, which estimates the net change in downstream emissions from the management of the remaining MSW (NETDOWN), is insignificant, the LCA practitioner can use Eq. 4 to account for the impacts of *WasteMAP* LCA scenarios:

$$\mathrm{NETDOWN} = \mathrm{DOWN} - \left(\mathrm{REF} - \sum_{\mathrm{WPA}=1}^{n} \mathrm{DownTPS}_{\mathrm{WPA}} + \sum_{\mathrm{WPA}=1}^{n} \mathrm{DownAPS}_{\mathrm{WPA}}\right) \tag{5}$$

where, DOWN, which can be derived through a traditional MSW LCA, depicts the downstream environmental emission from a MSW management scenario that includes WPAs; DownTPS represents the downstream environmental emission from each reference flow of product systems targeted for removal; and DownAPS signifies the downstream environmental emission from each reference flow of alternate product systems that generate less waste.

The use of Eq. 6 is appropriate if the result from Eq. 5 is significant, indicating that there are substantial downstream impacts of the WPAs on the management of the MSW remaining in the waste treatment system, such as the impacts from preventing the generation of "problematic materials." Equation 6 is defined as follows:

$$\mathrm{WMP} = \mathrm{DOWN} - \sum_{\mathrm{WPA}=1}^{n} \mathrm{UpTPS}_{\mathrm{WPA}} + \sum_{\mathrm{WPA}=1}^{n} \mathrm{UpAPS}_{\mathrm{WPA}} \tag{6}$$

where, as in Eq. 4, *WMP* represents a particular environmental emission from a *WasteMAP* LCA scenario that includes WPAs, UpTPS signifies the upstream environmental emission from the product systems targeted for removal, and UpAPS represents the upstream environmental emission from the alternate product systems that generate less waste.

For managing the same MSW, Eq. 7 of the *WasteMAP* LCA is used to estimate the net environmental emissions attributed to the implementation of waste prevention activities (WP):

$$\mathrm{WP} = \mathrm{DOWN} - \mathrm{REF} - \sum_{\mathrm{WPA}=1}^{n} \mathrm{UpTPS}_{\mathrm{WPA}} + \sum_{\mathrm{WPA}=1}^{n} \mathrm{UpAPS}_{\mathrm{WPA}} \tag{7}$$

Equation 7 not only allocates the net change in upstream emissions to the WPAs, but also the net downstream environmental emissions, which would include possible changes in the management of the MSW not subject to waste prevention.

The LCA practitioner may apply the LCA system boundary "cut-off" approach, used to account for the net burdens of recycling in the popular *EcoInvent* database (Frischknecht and Jungbluth 2007), in place of the "avoided burden" method adopted in Eqs 4, 5, 6, and 7. This is

accomplished by omitting the upstream component of the variables associated with the targeted product systems, thus affecting the variables *TPS* and *UpTPS*.

6 Discussion

When selecting a method to evaluate the environmental performance of residential waste management systems which include waste treatment, diversion, and prevention activities, the LCA practitioner has several options. Consequential LCA is appropriate when focussing only on the life cycle effects of a change in the quantity of waste managed. Product LCAs are justified if the focus of the LCA is to compare the emissions from two product systems providing equivalent product services, with one generating less residential waste than the other. Alternatively, the LCA practitioner can use the method of the *WasteMAP* LCA to compare within one system boundary all of the components of the waste management hierarchy, including WPAs and waste treatments, so that they are regarded as functional equivalents in managing MSW. This would permit the LCA practitioner to identify in the LCA results the burdens and avoided burdens attributed to waste prevention, recycling, biological, and thermal treatments, as well as landfilling, within a particular MSW management system. Should the product systems targeted for prevention by the MSW manager supply different product services measured with one or more secondary functional units, *WasteMAP*'s Eq. 4 is appropriate. However, if the WPAs have significant impacts on the management of the remaining waste streams, *WasteMAP*'s Eq. 6 should be employed.

The application of the *WasteMAP* method may possess a number of limitations, including the potential to increase the amount of error in the results due to the expansion of system boundaries. Error can also arise from assumptions associated with the functional equivalence of product services, such as assigning overly narrow functionally equivalent comparisons (Reap et al. 2008) for the secondary functional units of the *WasteMAP* LCA. It may, therefore, be of use to survey the target population to generate an estimate of the percentage of consumers that considers two product systems to be substitutable or a certain product service to be unnecessary. The functional equivalence assumption for a particular WPA may not be appropriate beyond a certain threshold. The LCA practitioner would need to distinguish between the substitutability of two product systems and the preference for one product system over another due to differences in the perception of quality, esthetics, or other properties.

Some MSW streams are known to be responsible for the contamination of various waste material feedstocks for recycling or for biological treatment. For example, although the biodegradable plastic, PLA, can be recycled, it cannot be combined with other recyclable plastics without harming the existing plastics recycling systems (Franklin Associates 2006). MSW managers may wish to evaluate MSW management scenarios that target the prevention of such waste streams to obtain downstream efficiency benefits. The *WasteMAP* method is also suited for such an evaluation: comparing the environmental performance of the reference MSW management scenario with one that lacks particular waste streams.

In advance of conducting an LCA based on the methods associated with *WasteMAP*, it would be wise to evaluate the waste prevention potential of a MSW management system and the potential effectiveness of various measures to implement WPAs. Additional research could also be undertaken to explore the extent to which the implementation of WPAs has decreasing returns to scale and whether or not there would be a greater waste prevention potential from cities with a larger per capita production of waste.

Income rebound effects may shrink the potential environmental and human health benefits of waste prevention policies (Takase et al. 2005). For instance, an increase in production efficiency lowers the cost of a good, thus freeing up consumer income to purchase other goods, possibly resulting in an overall increase in consumption (Takase et al. 2005). It may be possible to take this effect into account by grafting a relatively simple financial model onto the LCA and expanding its system boundaries. This model, which is consequential in nature, would be used to estimate the additional waste and environmental and human health impacts generated due to the expected marginal increase in consumer income.

7 Conclusions

While allowing the LCA practitioner to reap the data collection savings associated with streamlining the LCA, fixing the "cradle" of LCAs of MSW at waste generation limits the utility of the LCA to waste managers and policy makers due to the exclusion of waste prevention activities. System boundary expansion and the introduction of an additional type of functional unit permit the *WasteMAP* LCA to be applied to a wider array of possible waste management scenarios, including those which incorporate waste prevention. *WasteMAP*, unlike the traditional LCA of MSW, possesses the advantageous capability of evaluating the validity of the hierarchy of waste management, a resilient concept that continues to evince a significant influence on waste management policies.

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